arXiv:1301.7331v1 [physics.hist-ph] 30 Jan 2013

V. M. Slipher and the Development of the Nebular Spectrograph

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Abstract. Vesto Melvin Slipher was the first astronomer to clearly define the factors that determine the "speed" of a nebular spectrograph. This brief historical summary recounts the way these ideas developed and how Slipher's early work on galaxy Doppler shifts was so quickly extended in the 1930s when Milton Humason and Edwin Hubble at Mt. Wilson Observatory began to push the velocity-distance relationship to such a depth that no one could doubt its cosmological significance.

1. Early Spectroscopes and Spectrographs

Starting with the invention of the optical spectroscope in 1814 by Joseph Fraunhofer, and continuing for many years into the era of the first astronomical spectrographs, no one gave serious consideration to the consequences of preferentially selecting the f/ratio–or equivalently the focal length–of the last imaging lens in the system (the camera lens in a modern spectrograph). We know today that a spectrograph with a short focal length camera is key to detecting extended low surface-brightness objects, i.e. nebulae, and that longer focal length cameras work well on higher surface-brightness objects like stars, the Sun and planets.

The state of spectroscopy in 1890-1894 is beautifully summarized in the book entitled *Astronomical Spectroscopy* written in German in 1890 by Julius Scheiner at Potsdam Observatory but translated into English in 1894 by Edwin Frost (Scheiner 1890). This was the first textbook on the subject, and as mentioned above, there is no discussion in this book on how to optimize the performance of a spectrograph by selecting the spectrograph camera optics. Spectroscopy was rapidly evolving in this period of time as evidenced by papers published in the *Astrophysical Journal* (e.g. Wadsworth (1895) and references therein).

Given the leadership shown by Scheiner in astronomical spectroscopy, perhaps it is not surprising that he was the first to photographically detect the absorption line spectrum of the Andromeda nebula (Scheiner 1899). His detection of Andromeda, and an even earlier but less certain one by Huggins (1899), were both referenced by Fath (1909a) when Fath published the results of his Lick Observatory Ph.D. thesis research. In this early work Fath detected photographically the spectra of six spiral nebulae, with Andromeda being one of the six.

The theme of this brief historical contribution is to highlight the necessity of using a fast spectrograph camera if the aim is to detect the absorption line spectrum of spiral galaxies. In his spectroscopic detection of Andromeda, Scheiner (1899) used an f/3 mirror system (most likely in the configuration of a Zollner ocular spectrograph as described on page 81 of his textbook). Fath (1909a) used an f/3 spectrograph camera

lens in his work at Lick Observatory and later an $f/2$ lens when he worked at Mt. Wilson, and Vesto Melvin ("V.M.") Slipher employed an $f/2.5$ commercial camera lens in the spectrograph he used to detect spiral galaxy spectra for measuring Doppler shifts.

2.   Brashear Spectrographs for Lick and Lowell Observatories

In the early 1890s W. W. Campbell, one of the great stellar spectroscopists of the late 19th and early 20th centuries, designed Lick Observatory's Mills spectrograph in conjunction with its manufacturer, the John A. Brashear Company of Pittsburgh. The Mills spectrograph arrived at Lick Observatory in 1894 and was set to work collecting photographic spectra of stars. Soon after the Mills spectrograph was delivered, Percival Lowell approached John Brashear to build a spectrograph for the Lowell Observatory 24-inch refractor. These two spectrographs share many of the same design characteristics. In particular, the spectrograph cameras were $f/14$ in both instruments, and both accommodated three prisms allowing them to work at high spectral dispersion.

Percival Lowell hired V.M. Slipher in 1901, fresh out of Indiana University, to commission the Brashear spectrograph on the Lowell Observatory 24-inch refractor (Hoyt 1980; Smith 1994). Slipher's first scientific assignment was to measure the rotation rate of the planet Venus, and before starting this more difficult task, Slipher confirmed his techniques by obtaining spectra with the Brashear spectrograph of the planets Jupiter and Saturn. Since all three planets–Jupiter, Saturn and Venus–are high surface brightness objects, the Brashear spectrograph was able to make the necessary detections in the original design configuration. Slipher successfully determined an upper-limit to Venus' rotation as no rotation could actually be detected. He finished this work by 1903.

Throughout the period from 1901 to 1910, V.M. Slipher interspersed his investigations of planetary rotation with spectroscopic and radial velocity measurements of stars. One of his papers was a systematic investigation of radial velocity standard stars with the Brashear spectrograph (Slipher 1905). During this same period he published approximately 30 papers in journals and in the Lowell Observatory Bulletin.

As documented in their correspondence, Percival Lowell began to encourage V.M. Slipher starting in 1909 to work in an entirely new area of research: to determine the spectroscopic properties of the light coming from the outer parts of spiral nebulae. As reported by Smith (1994), Lowell was motivated by the idea that spiral nebulae might resemble proto-solar systems and that the spectra from the outer regions of spirals might resemble the spectra of the giant outer planets. All observations of the outer regions of spirals in this era were destined to be unsuccessful. Venus and Jupiter have an approximate surface brightness of 1.2 mag/arcsec^2 and 5.4 mag/arcsec^2, respectively. Bright galaxy nuclei have a surface brightness in the range of 10 to 12 mag/arcsec^2, and yet the outer parts of spirals (the region of Percival Lowell's interest) have a surface brightness in the range of 21 mag/arcsec^2. The 15 magnitude difference in surface brightness between Jupiter and the outer parts of spirals is a factor of 1 million in terms of flux received at the photographic plate. The surface brightness difference between Jupiter and the nuclei of spirals–which Scheiner, Fath and Slipher all detected–was a factor of several hundred.

3.   Fath and Slipher Extend the Work of Scheiner

Percival Lowell was not the only astronomer who had an interest in the spectra of spiral nebulae. Others speculated that spiral nebulae were galaxies of stars and that their spectra could reveal key evidence in this regard. By 1907 W. W. Campbell at Lick Observatory encouraged Ph.D. student Edward Fath to begin spectroscopic observations of spiral nebulae and globular clusters with the 36-inch Crossley reflector. Fath's spectrograph went together quickly because it was assembled in a wooden box. It was so crude that adding spectral comparison lines to any spectrum meant that the spectrograph had to be completely removed from the telescope. These characteristics precluded Fath from measuring reliable radial velocities. But much to his credit, Fath's new spectrograph at Lick Observatory used a fast spectrograph camera lens: f/3.04. By 1908 he had succeeded in detecting spectral lines (both absorption and emission) in a few galaxies, and by 1909 he had published his first results (those based on his Ph.D. thesis work). Eventually, Fath published three papers documenting observations for a total of ten galaxy spectra (Fath 1909a, 1911, 1913).

Those who read Fath's original work from 1909 can recognize that his observations raised as many new questions as they solved. He did see absorption lines from the constituent stars in the spirals, but the spectra of spirals also showed emission lines from Seyfert galaxy activity. The original data are described in Fath (1909a). These stand on their own and are easy to understand in a modern context, but his interpretation of his own observations (Fath 1909b) reflects the great uncertainty that existed in that era regarding the nature of the spiral nebulae.

After graduating with his Ph.D. degree, Fath accepted a position at Mt. Wilson Observatory where he continued his work on spiral nebulae by building another spectrograph for the newly completed Mt. Wilson 60-inch telescope. His second spectrograph was no more robust than his first. Slipher and Fath met for the first time at Mt. Wilson Observatory in August, 1910, approximately one year after Fath's first paper on spiral nebulae had been published. They were both attending a large astronomical gathering entitled the *4th Conference of the International Union for Cooperation in Solar Research*. Soon after they met at this conference, they began an intermittent correspondence that lasted three years. Based on the correspondence between Fath and Slipher (available in the Lowell Observatory Archives) and on the timing of Slipher's subsequent work, it appears that their meeting at Mt. Wilson helped to spur Slipher into action. With the mechanical assistance of Stanley Sykes, Slipher modified the Brashear spectrograph allowing it to accept a fast spectrograph camera lens. Because Fath's spectrographs were neither rigid nor stable enough to provide Doppler shifts, a perfect opportunity was open for V.M. Slipher to apply to the spiral nebula problem everything he had learned about Doppler shifts and the Brashear spectrograph during the previous ten years. Slipher purchased an $f/2.5$ commercial camera lens from Voigtlander and installed it in the Brashear spectrograph. Figure 1 shows the new equipment in its final assembled form.

Slipher's first target was the Andromeda nebula, and his first opportunity to use the new spectrograph camera came in December 1910. His early spectra showed some absorption lines, but the results were not optimal. In a letter to Fath dated February 8, 1911, Slipher [1] estimates that the sky was so poor during these exposures that his equiv-

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[1] Slipher (1911)

Figure 1.   The collimated beam from the Brashear spectrograph enters from below through the hole on the lower left, passes through the prism (visible under the large triangular plate), and proceeds to the $f/2.5$ Voigtlander lens that is mounted inside the large brass cylinder in the upper right. The photographic plate holder is held under two mounting screws on the upper right hand side at the focal plane of the Voigtlander lens.

alent total exposure time in 1910 amounted to no more than four hours. V.M. Slipher tried again in the fall of 1911 and found that his second effort was also unsuccessful because he had used a prism with too low a dispersion and a slit that was too narrow (relative to the grain in the photographic emulsion). By fall 1912, he was using a higher dispersion prism (i.e. a prism of denser glass) and a wider slit. Both the 1911 and the 1912 configurations gave the same spectral resolution, but the latter combination produced a better image of the slit on the photographic emulsion (Slipher 1913). It was at that point (September 17, 1912) that on an exposure lasting one full night he obtained his first spectrum of Andromeda with an image that could be measured for the Doppler shift. He followed up rather quickly with more exposures, the first pair each lasting two nights (November 15+16 and then December 3+4) and the final one lasting three nights (December 29+30+31). All of the spectra taken in late 1912 yielded measurable Doppler shifts.

In his early papers on Andromeda, Slipher made no mention of the slit width he used in the spectrograph. But in Slipher (1917) he states that his prism worked at 140 Å mm^{-1} and that the equivalent slit width was 0.06 mm. I interpret this to mean that the slit projects onto the plate with a width of 0.06 mm, and working backwards with the optical properties of the spectrograph and the 24-inch Lowell refractor, this

means that on the sky the slit width was 8.25 arcsec. Fath (1909a) states that on the Crossley reflector, he used a slit width of 0.15 mm, and this converts to an angular width of 5.8 arcsec. So both the Fath and Slipher instruments were working as nebular spectrographs at very low spectral dispersion with wide slits. Only in this way could they attain adequate signal-to-noise ratios on the final photographic image.

4. The Defining Properties of Nebular Spectrographs

Although Scheiner and Fath were the first to use short focal length camera lenses in their spectrographs thereby making the absorption lines of spiral nebulae detectable, V.M. Slipher went a step further in an effort to determine what parameters–for both the telescope and the spectrograph–were responsible for optimizing the detection of low surface brightness objects. Slipher's conclusions first appeared in a letter to Fath dated February 8, 1911:

> the ratio of the aperture to focus of the telescope objective has nothing to do with its usefulness for spectrum work on the extended surface ... Intensity of the image on the slit of course does not count but (the) intensity of spectrum on the sensitive surface does and it is only the camera that determines this.

In this correspondence Slipher asks Fath directly whether spectra of spiral nebulae taken with the Mt. Wilson 60-inch telescope are significantly better than those taken with the 36-inch Crossley reflector, but Fath was unable to give any clear evidence one way or the other. He simply replied that the two spectrographs he used were sufficiently different that he could not tell. Of course, Slipher was working with the Lowell Observatory 24-inch refractor with a long focal length objective, and this matter was of key importance to him.

V.M. Slipher's design specifications for nebular spectrographs were repeated in a very clear manner in all three of his papers on the Doppler shifts in galaxy spectra: Slipher (1913), Slipher (1915), Slipher (1917). These ideas became of central importance to the later work of Milton Humason (1931), work that provided the foundation for Edwin Hubble's extension of the velocity-distance relation beyond the initial forty-one Doppler shifts determined by V.M. Slipher (those 41 were originally published as a complete list in Eddington (1923)). It is emphatically true that without Slipher's initial 41 Doppler shifts and without his clearly stated design principles for nebular spectrographs, Humason and Hubble's work on the velocity-distance relation would have suffered a considerable delay.

By the 1930s, the key role of the spectrograph camera's f/ratio was recognized by the staff of the Mt. Wilson Observatory. The first spectrograph given to Humason for redshift work used an f/1.43 camera lens. Later Humason had access to a series of extremely fast camera lenses with f/0.59 built specifically for the Humason-Hubble redshift program (Rayton 1930). The ease with which Humason pushed to higher redshifts on the Mt. Wilson 100-inch telescope, far beyond those of Slipher, was almost entirely dependent on the speed and excellent optical quality of the Rayton spectrograph camera lens and had little to do with the 100-inch telescope aperture.

A modern re-statement of Slipher's nebular spectrograph design concepts was made by Mt. Wilson Observatory's Ira Bowen in 1952 when he wrote in a more complete way (for both nebular and stellar sources) how the "speed" of a spectrograph

depends on key parameters like the diameter of the telescope objective, the f/ratio of the spectrograph camera lens, and (for stars) the slit width relative to the seeing disk (Bowen 1952). For a true nebular spectrograph, exactly as V.M. Slipher originally stated, Bowen found the "speed" of detection (i.e. the energy cm^{-2} s^{-1} received at the detector) is completely independent of the diameter and focal length of the telescope objective and can be written as follows:

$$\text{"}speed\text{"} = (\text{object surface brightness}) \, w'P/F^2 \tag{1}$$

where w' is the projected slit width in millimeters at the detector, P is the spectral dispersion in Ångstroms mm^{-1} at the detector, and F is the focal ratio of the spectrograph camera lens. For example, if we assume that $w'P$ (the number of Ångstroms sampled by the spectrograph slit at the photographic plate) was the same in Slipher's nebular spectrograph as it was in Humason's spectrograph with the Rayton lens, the relative "speed" of detection between their two systems when working on the same object is the square of the ratio of the two cameras f/ratios:

$$(2.5/0.59)^2 = 18. \tag{2}$$

So it is not surprising that the Humason-Hubble team pushed deeper into the Universe when they confirmed in the 1930s the linear velocity distance relation.

Those who want to see a more complete discussion of the speed of spectrographs and their key design parameters might look at the somewhat updated description in Bowen (1964) or at monographs on instrumentation design like *Astronomical Optics* by Schroeder (1987). The use of the symbols w' and P above are taken from Schroeder (1987), and I have omitted from the simple equations above several parameters, for example the end-to-end optical system efficiency and the "anamorphic magnification" in the spectrograph beam, because these two parameters will be somewhat similar from one optical system to the other.

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